NATIONAL NUCLEAR LABORATORY

Technical Review

2013

Delivering the best nuclear science and technology solutions in the world

Integrity, Innovation and Impact

Key Highlights:

- Broad support for the UK and international nuclear industry
- Key support for high level Government reports
- Continued work with academia and other key partners
- Outstanding work on innovative projects such space batteries

Contents

Technical Review

Introduction by Graham Fairhall, Chief Science and Technology Officer

Welcome to the UK National Nuclear Laboratory's 2013 Technical Review. This is the second time we have published this overview of some of our key technical work. The past 12 months or so have seen significant changes for us and the broader nuclear industry. We are proud to have delivered many outstanding technical projects for our customers to help them fulfil their business objectives.

The past 12 months have seen reviews of nuclear research and development at the highest levels in the UK. The House of Lords Science and Technology Select Committee reported last October and the Ad Hoc Nuclear Research and Development Board led by the then UK Government Chief Scientific Adviser, Sir John Beddington, reported earlier this year.

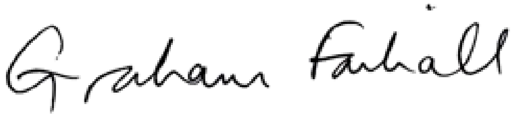
NNL made significant contributions to both these bodies. You can read more about this on pages 24-25.

Our work covers the breadth of the nuclear industry, supporting customers in the UK and increasing our international presence. In order to deliver science and technology solutions for our customers, we often collaborate with universities and other partners. You can read more about that on pages 26-27.

Projects reported in this Technical Review include our ongoing support to high level waste management at Sellafield and to the UK nuclear power industry via our Post Irradiation Examination work at Windscale. We also report on the efforts we make to support fuel manufacture and our international work including helping to retrain former nuclear weapons scientists from Iraq.

I am also pleased to provide information about the work we have been doing for the European Space Agency in helping to develop space batteries. This is a very exciting project using cutting edge science to help develop suitable power sources for long-term space missions. This is a great example of taking nuclear science and technology and applying it in another industry. You can read more about this project on page 22.

I hope you enjoy our Technical Review. I am certainly proud of what we have achieved and delivered for our customers and stakeholders this past year. If you have any comments or feedback, please email me at customers@nnl.co.uk.



Graham Fairhall
Chief Science and Technology Officer

Who We Are and What We Do

NNL's principal activity is the provision of technology services across the nuclear fuel cycle

The Company provides technical support and services to customers in three key areas of the nuclear fuel cycle:

Waste Management and Decommissioning

Products and services are focused on supporting customers via the development and application of technologies and techniques that assist with the ongoing and eventual decommissioning of nuclear facilities. The business comprises the skills and facilities required to cover the full dimension of waste management and decommissioning projects. Key areas include environmental and effluent management, measurement and analysis and waste immobilisation technology. Programme integration and project management also form a key part of the service portfolio.

Fuel Cycle Solutions

The business is focused on providing fundamental technical solutions to customers in the nuclear industry. It covers fuel cycle performance and technology development, spent fuel disposition and plant integrity. Other areas covered include nuclear security, safety management and engineering services. An advanced modelling and simulation capability is also a key part of the directorate.

Reactor Operations Support

As the profile of nuclear generated energy continues its resurgence in the UK and internationally, NNL provides key services to reactor operations. These include Post Irradiation Examination (PIE) and performance of fuel, components and graphite. The business also offers services covering power station chemistry, endoscopy and metallography.

Our Customers

Our largest customers are the Nuclear Decommissioning Authority (NDA), Sellafield Limited, Magnox Electric Limited, Springfields Fuels Limited, EDF Energy and the Ministry of Defence.

The Company also serves other customers in the UK, USA, Japan, Europe and Middle East.

Investing in the Future

A key part of our work is maintaining and developing critical skills and attracting talented new people to the industry.

One way in which we do this is through an extensive - £1 million a year - investment in a self-funded Research and Development programme.


IRAQ
Hamadan
An Najaf
الله أكبر

Crystallisation within Highly Active Transfer Pipes

NNL investigated how a change in storage temperature of Highly Active Liquor might impact the risk of solids crystallisation

Highly Active Liquor (HAL) is buffer stored in Highly Active Storage Tanks (HASTs) prior to feeding to the Waste Vitrification Plant where it is turned into a glass matrix for longer term storage. The HAL transfer is undertaken by means of steam ejectors and pipes.

A reduction of HAL storage temperature within HASTs was under consideration to reduce corrosion. However, the potential downside of this is the increased likelihood of solids crystallisation in the transfer pipes which would create significant problems. NNL was asked to investigate the impact of reducing HAL storage temperature from 55°C to 45°C in the transfer pipes and to determine the likely increase in risk of solids crystallisation.

NNL developed a simple heat transfer model. Through examining several scenarios, we were able to confirm to our customer that the HAL temperature at the pipe outlet was higher than in the storage tank. As a result, we were able to prove that reducing the HAL storage temperature from 55°C to 45°C does not result in an increased risk of crystallisation of solids within transfer pipes. This work was valuable to our customer in putting together a strong case for the temperature reduction and in turn lowering corrosion rates, prolonging plant life and saving money.

Supporting Iraq

NNL has provided training for a number of ex-weapons nuclear scientists as part of a programme to help them support civil nuclear activities back home

NNL completed the training of 40 individuals via a technical training programme and complemented this with a UK practical phase held at NNL, the Low Level Waste Repository and Sellafield Limited facilities.

20 Iraqi scientists undertook a further intensive week long course focused on applied learning through observing waste characterisation, handling, waste management and disposal practices first hand. A programme of lectures, site visits and practical exercises ensured the delegates were able to apply their previous training and consider how this was to be applied in the decommissioning and legacy waste activities underway within Iraq.

Magnox Sludge Storage Silos Beta Gamma Waste Project

NNL provided extensive, quick and efficient support to ensure our customer was able to meet key performance targets

On the Sellafield site, the Windscale Advanced Gas-cooled Reactor (WAGR) is nearing the end of its decommissioning phase. As this plant has a grouting facility and a waste store, Sellafield Ltd have identified the WAGR facility as a suitable option for the receipt, encapsulation and storage of some of the historic Miscellaneous Beta Gamma Waste from the Magnox Sludge Storage Silos plant. This is known as the Beta Gamma Waste Project.

As part of this process, MBGW sealed containers would have to be removed from skips and disrupted before being encapsulated in waste baskets. This disruption is necessary to enable the egress of can liquids and gases as well as providing access for the grout.

Sellafield Ltd approached NNL to undertake a series of independent 'proof of concept' trials aimed at increasing the understanding of the handling, disruption and grouting of the MBGW waste. The objective of the trials was to demonstrate an appropriate level of technology readiness.

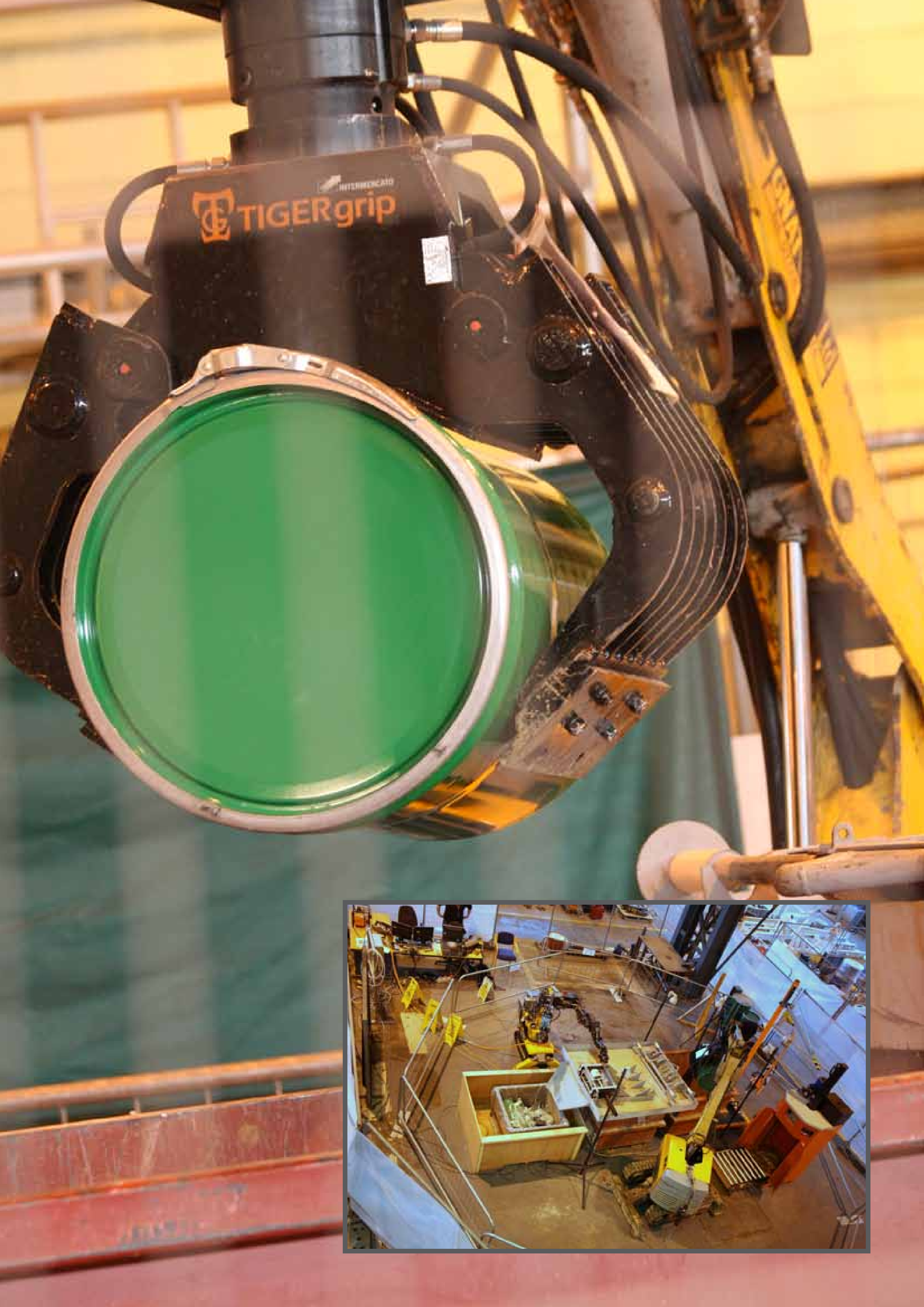
The project involved the optioneering, design, procurement, manufacture, build and operation of remote equipment on a full scale test facility at NNL's Workington Laboratory.

The project started with optioneering exercises to identify potential technologies and methodologies for conducting the can disruption and handling tasks. Following a methodology study and assessment of these various techniques, a design and procurement phase was undertaken for the more viable options. The selected equipment was then assembled into a full scale mock-up to enable remotely performed trials to prove the viability of the techniques.

The developed solution utilised a linear layout of processing equipment with a heavy duty Remotely Operated Vehicle (ROV) to handle the heavy and bulky waste items (up to 400 kg) and a light duty ROV, mounted with two hydraulic manipulators, for handling the smaller waste items, disruption tools, waste sorting, segregation and general housekeeping duties.

Although the main disruption tool, a hydraulic shear, was very successful in easily and rapidly disrupting all the waste cans tested regardless of their size, shape or contents, a number of other cutting tools were also successfully demonstrated. In addition, two compactors were trialled as a means of compacting and piercing the cans to successfully release liquor and gas.

All the handling and disruption trials were performed remotely, with the assistance of a CCTV system, while the operators were located at a remote work station. The degree of disruption was assessed and confirmed as successful by finally grouting the waste items in moulds and subsequently sectioning and examining them.


TIGERgrip

Hunting Radium Contamination at Former RAF site

NNL was asked to help determine whether World War II operations had left radium contamination at a site targeted for a flood risk management scheme

NNL was asked to support a site investigation at Daniels Brook in Gloucester, by providing a method for the radiological screening of a number of soil cores sampled at various points across the site. Daniels Brook is a site targeted by the Environment Agency for a flood risk management scheme, involving a large amount of excavation work at the site.

The land surrounding the site was previously occupied by RAF Quedgeley, operational from 1915 until its closure in 1995. The Ministry of Defence recently announced that the site was potentially contaminated with radium (Ra-226) as a result of World War II activities - making instruments luminescent for night time operations.

With radium contamination identified as a potential risk at Daniels Brook, the primary site investigator, White Young Green Group Ltd (WYG) approached NNL to provide advice and comment on their proposed approach to managing the contamination risk.

WYG proposed using a hand held 'radalert'. Following a full review, NNL's view was that this equipment would not be sufficiently sensitive to detect what were expected to be very low levels of activity. Therefore, NNL recommended an alternative approach using a sodium iodide detector to undertake in-situ gamma spectrometry on selected samples.

As a result of these discussions, WYG commissioned NNL to undertake the in-situ radiological screening of the soil cores obtained at various locations across the site. Our aim was to establish whether any radiological contamination was present in the ground from where the soil cores were obtained.

NNL undertook initial monitoring using health physics instrumentation with no radiological contamination confirmed. A selection of soil cores were counted in-situ, using a portable sodium iodide detector to identify the presence of Ra-226 and its daughter products using gamma spectroscopy. Again, we were able to show that there was no evidence of soil contamination by Ra-226.

The in-situ monitoring work carried out by NNL confirmed the soil samples obtained by WYG were free from radiological contamination by Ra-226 and its daughter products. As a result, this particular contaminant could be ruled out of the site investigation at Daniels Brook.

The benefits of in-situ radiation monitoring are that it reduces the need for time consuming laboratory analysis by providing the customer with an immediate answer in the field, at a reasonable cost.

With radium contamination confirmed on up to 15 former RAF sites across the country by the Ministry of Defence, it was important that this work was carried out accurately and effectively.

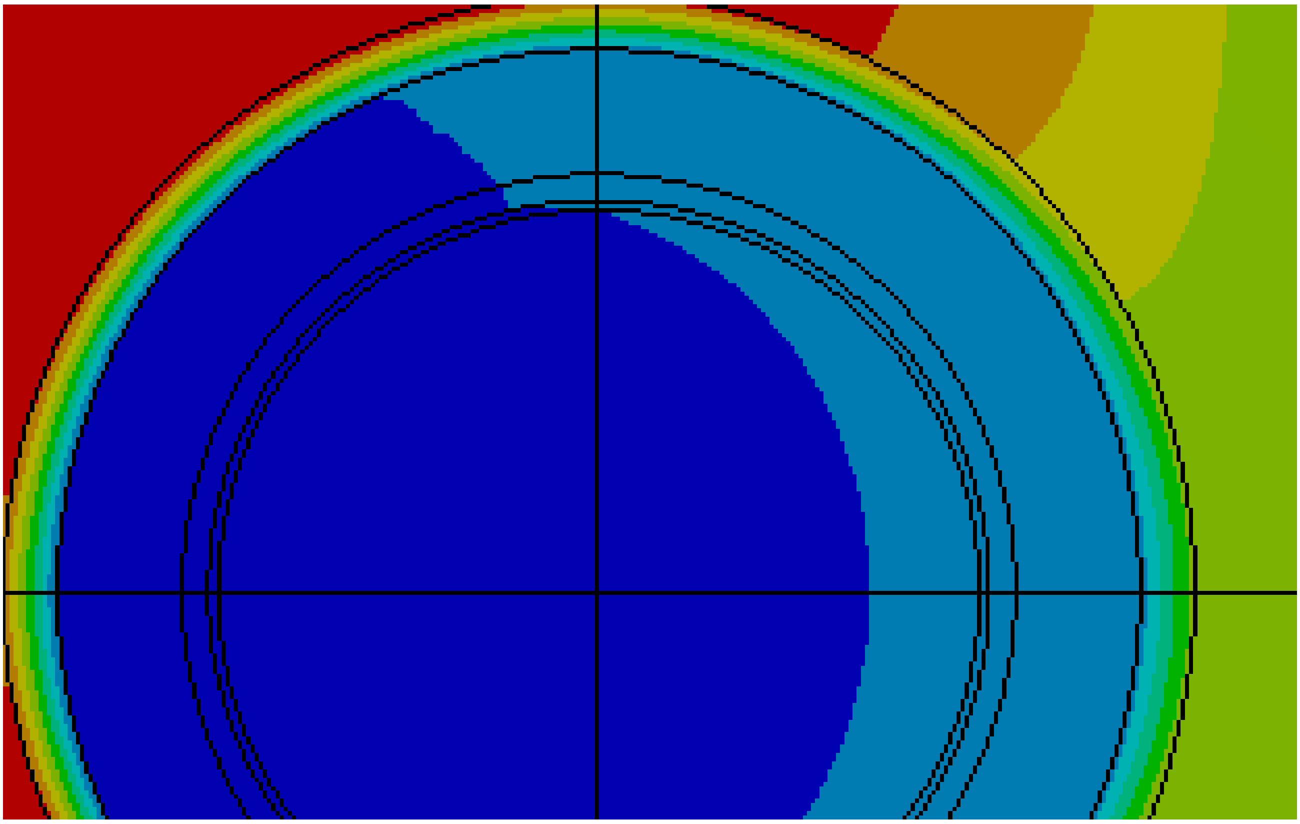
Strategic Modelling of Future HLWP Throughputs

NNL's modelling work was used to underpin a £250 million decision and ensure safe, successful operations

The aim of the High Level Waste Plant (HLWP) is to evaporate highly active raffinate from reprocessing, store the concentrate and produce vitrified containers. As the plant approaches the end of its life, it is necessary to predict and justify the requirements for new infrastructure projects (such as Evaporator D). Due to the costs associated with construction and the forecast decommissioning costs of Evaporator D, the NDA required justification for the project to proceed.

NNL developed a high level process model to examine future arisings to HLWP and the impact of Post Operational Clean Out (POCO) on downstream operations. The model was designed to be simple, robust and therefore able to simulate a wide range of options. It was concluded that, without Evaporator D, the additional burden associated with POCO on the vitrification plant would not be manageable. Furthermore, a shortfall was predicted between the total challenge to the vitrification plant and the total capacity of the plant.

This high profile work has underpinned a £250 million decision and has resulted in NNL being positioned to contribute strongly to future POCO and decommissioning design packages.



Residues Assessment

NNL's Residues Phased Methodology is supporting customers' requirements to process significant quantities of their residues

The need to process residues is long established and growing as more attention is being paid to reducing liabilities on nuclear sites. The uranium is recovered from manufacturing by-products and decommissioning arisings which allows the uranium to be returned to the fuel cycle and the waste to be sent for standard disposal.

Prior to processing the residues, a phased assessment methodology is used to determine how and where to process them most cost effectively. This is called the NNL Residues Phased Methodology and has been applied extensively across a wide range of different customers' residues over the past year.

The methodology consists of:

- Gathering of historic information to gain an initial understanding of the residue
- Sampling and characterisation using instrumentation to increase this understanding prior to full scale laboratory work
- Performing a standard acid leach test to determine whether currently available routes can be used
- Developing a specific route if there is no currently available route
- Recommending the processing plant and route

This year the residues have varied from:

Bauxalite, dirty oxide powders, pickling liquors, uranium oxide sludge and slurries from decommissioning operations dissolver cake, drain diggings and sump liquors, dry blended enriched uranics containing glass fibre, aluminium and oil, uranium oxides with unusual bulk additives and containing significant concentrations of transuranics and fission products.

This methodology has been applied to over 70 different residues this year, enabling routes to be recommended to our customers and over four tonnes of residues to be processed at NNL's Preston Laboratory this year.

Opposite: Main Rig Hall at NNL's Preston Laboratory


No. SM001653
SWL 10t

Using Metallography to Understand Advanced Gas-Cooled Reactor Fuel

NNL leads the way in the UK in terms of undertaking Post Irradiation Examination of Commercial Advanced Gas-cooled Reactor fuel

Metallographic examination is routinely undertaken after non-destructive Post Irradiation Examination (PIE) of Commercial Advanced Gas-Cooled Reactor fuel (CAGR). Within the UK, this work is performed by NNL at our Windscale Laboratory. Some of our recent work has compared and contrasted the common microstructural features within water and gas-cooled systems.

Windscale Laboratory has been carrying out PIE for many years and in that time has worked on commercial reactor fuels, novel fuels and irradiated reactor components. Much of the development work for UK fuel was undertaken and current UK reactor operations are supported by work carried out in the active cells at NNL's Windscale Laboratory.

NNL recently provided an overview of the metallographic preparation routes for CAGR materials and the microstructure of the fuel pin materials. The hollow bore ceramic uranium oxide (UO_2) fuel used in CAGR reactors is very similar to the solid fuel generally used in water reactors. However, UK reactors use a gas coolant as opposed to liquid coolant and moderator, which means operating temperatures are relatively high when compared to water reactor systems. Another key difference is the fuel pin cladding material, as UK gas reactors use a 20%Cr:25%Ni:Nb stainless steel as opposed to Zircaloy.

The microstructural changes observed, such as cracking of the fuel pellet and the precipitation of phases in both the fuel and cladding, all contribute to an understanding of material behaviour under irradiation. Although quantitative data on composition is not available via the optical metallography route, the distribution of, for example, fission gas bubbles in the fuel, further facilitates the assessment of irradiated material behaviour.

Safety Support at Springfields

NNL provides specialist safety management advice and support to the UK's premier manufacturer of nuclear fuel

Springfields Fuels Ltd (SFL) manufactures uranium hexafluoride and low enrichment uranium oxide fuels and intermediate products. The site also processes fuel cycle residues resulting from both Magnox and uranium oxide fuel production processes.

NNL provides a Safety Management service from its Preston Laboratory. We provide expert radiological, criticality and chemotoxic safety support to various plant modifications that SFL wish to make (both operational and engineered).

Over the past year, this support has ranged from ad-hoc technical advice and peer reviewing plant modification proposal forms to running and providing technical input into HAZard and OPerability (HAZOP) fault studies.

Once the appropriate fault identification processes have been carried out, NNL produce the required safety assessments, working closely with SFL to ensure that the safety solutions are As Low As Reasonably Practicable (ALARP) and fit-for-purpose.

We then follow up and support the implementation of the safety documentation by providing input into various plant processes as required (eg operating instructions, engineering justifications, clearance certificates and inspections).

SFL's strong safety culture relies on well-trained and knowledgeable people with a questioning attitude. To support this, NNL places a strong emphasis on providing focused, job-specific training as appropriate in support of any new modifications.

Cleaning up Molybdenum

NNL developed a new glass to help accelerate clean-up and reduce the number of containers required for waste storage

Post Operational Clean Out (POCO) of the Highly Active Storage Tanks (HASTs) prior to decommissioning will involve the removal of the HASTS' heels. These are enriched in caesium phospho-molybdate and/or zirconium molybdate solids. These clean-up operations will result in a high molybdenum stream which will be vitrified using the current Waste Vitrification Plant. In order to minimise the number of containers required for POCO, the incorporation of molybdenum needs to be maximised.

NNL developed a new borosilicate glass formulation containing calcium. This allows a higher incorporation of molybdenum through the formation of a durable $CaMoO_4$ phase, after the solubility limit of molybdenum in the glass has been reached. Vitrification of the high molybdenum feed in the presence of varying quantities of reprocessing waste liquor using the new glass formulation has been carried out in the laboratory. Recent experimental work has indicated that up to ~10 wt% MoO_3 could be incorporated without any detrimental yellow phase separation in the product glass but increasing the fraction of reprocessing waste which is likely to be present in the HASTs' heels was found to decrease the MoO_3 incorporation. The quantity of MoO_3 (wt%) which can be incorporated into the glass product is shown in the table below:

	Reprocessing Waste		
Reprocessing waste loading	Magnox	Blend (50 oxide: 50 magnox)	Oxide
0 wt%	10		
5 wt%	8.5	9.5	8.5
15 wt%	8	8.5	8.5
25 wt%	6.5	7	7

Electrochemical Treatment of Spent Decontamination Solutions

NNL's technology has the potential to provide a rapid and low effluent volume decontamination method for use on nuclear sites

The application of wet decontamination on nuclear facilities is often compromised by downstream complications. For example, issues with respect to the impact on abatement plant or corrosion of infrastructure. NNL, in partnership with CTech Innovation have developed a system, ELENDES, that enables the use of a wider range of aggressive decontamination reagents by providing a means of neutralising the waste decontamination solutions prior to discharge.

ELENDES is an electrochemical system for the treatment of decontamination effluents. It is capable of destroying organic complexants and liberating chloride and therefore rendering decontamination effluents compatible with effluent infrastructure on nuclear sites. The technology can be employed in small scale mobile plant or as an addition to centralised infrastructure if required.

This technology is being developed via a Technology Strategy Board funded project between NNL and CTech Innovation, which aims to establish the feasibility of removing 'problematic species' from spent decontamination agents using electrochemical cells.

ELENDES was developed using NNL's experience in the development of abatement systems, gained from over 30 years of operation and design support to key nuclear abatement facilities, coupled with electrochemical process design expertise from one of NNL's collaboration partners, CTech Innovation.

Active demonstration units will be employed in NNL's Central Laboratory with a view to developing pilot scale demonstration units. Example decontamination effluents will be provided for evaluation by key stakeholders.

The complete solution

ELENDES can be used as part of an Integrated Decontamination System which applies:

- remote characterisation techniques in order to fingerprint the contamination and optimise the decontamination reagents deployed
- low volume reagent deployment systems which allows the inventory of reagent to be minimised
- post treatment using process intensified abatement techniques developed within NNL

Skip Liquor Containment During Road Transportation

A tricky trial to ensure the safety of liquor transportation led to excellent feedback from one of our customers

Sellafield site is moving away from rail transport systems to transportation using the road network only. Several trials have been performed previously to assess the containment capability of liquors within a SEP Package waste skip when transported on the site rail system. The design of the hydrogen vent system on the waste skip has been optimised to prevent loss of liquor during rail transportation.

Trials were required to assess the capability of the hydrogen vent design to contain the liquors when transported on the Sellafield Site road network. A satisfactory outcome of the trials was to achieve a zero leakage criteria over a complete journey simulating the route conditions that would be experienced on Sellafield Site.

Trials were required to assess the impact of liquor loss from the skip under various fault conditions; liquor at various levels, skip lid dislodged and simulated skip lid seal damage. Trials were also required to confirm that the skip liquor containment capabilities are not compromised if the skip lid buffer units are not fitted to the skip lid.

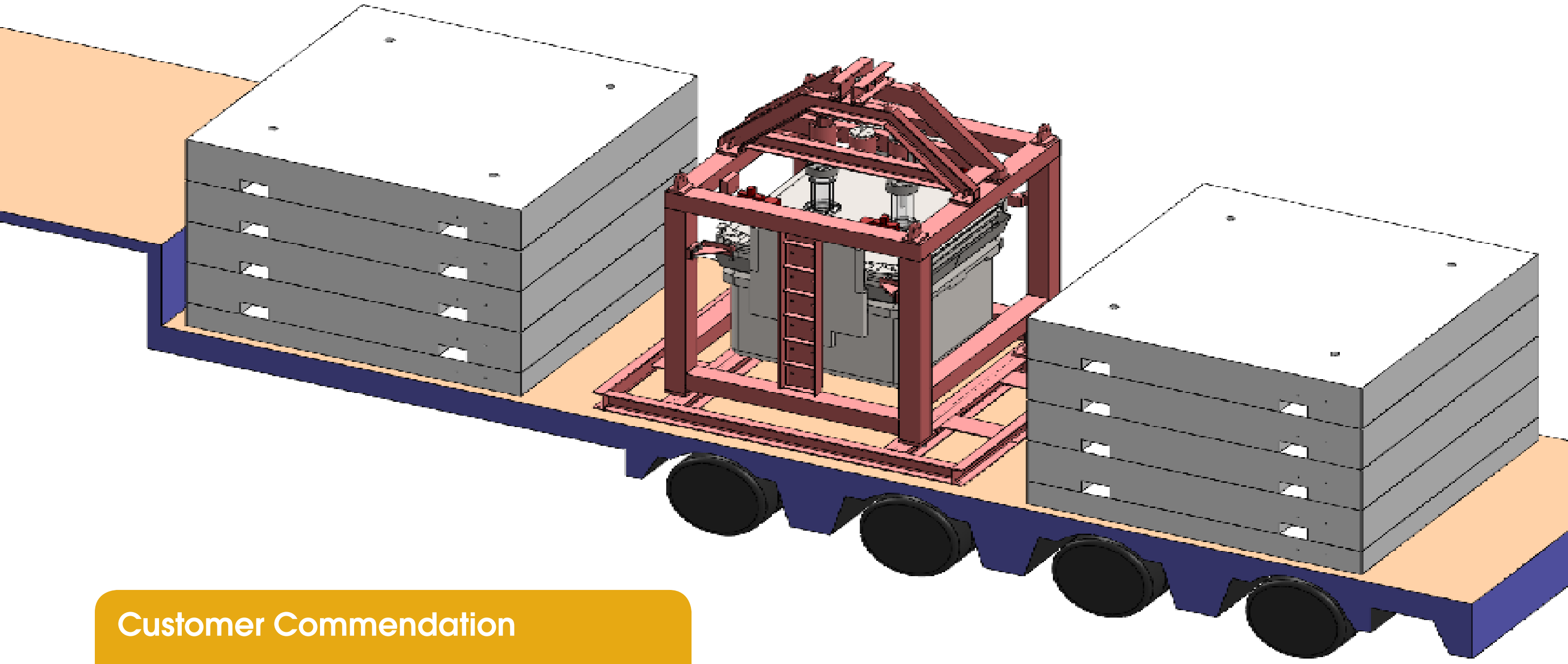
The original Skip Liquor rig was modified to client instructions to allow the test rig to be mounted onto a road worthy stepped trailer. Design was carried out to reduce the overall height of the main frame and incorporate jacking points into the frame legs. A Digital Video Recorder (DVR) and 4 high resolution cameras were mounted on the test rig to capture the real time events and a GPS system plotted the route taken. All Electrical equipment was chosen / designed to be powered by a high capacity 12 volt leisure battery via a regulator control/isolation box and monitored by a power consumption device.

The Elvington Airfield was hired for the location of the test track. A 1.6 Kilometre test track was set out which encompassed a selection of bends, straights and speed bumps to emulate the onsite transport route.

The 50 Tonne Skip Liquor rig was transported from the Workington Laboratory to the Elvington Airfield using 3 tractors and trailers. A contract lift was arranged at Elvington to lift the 44 Tonnes of concrete ballast blocks onto the Skip Liquor rig trailer.

Four weeks of trials with the Skip mounted in two different directions, mounted level and inclined, with the skip lid dislodged and simulated skip lid seal damage are were successfully undertaken to prove the feasibility of containment. Data retrieval took the form of a DVR capturing video pictures from the 4 high resolution cameras, data from the GPS system and digital still images.

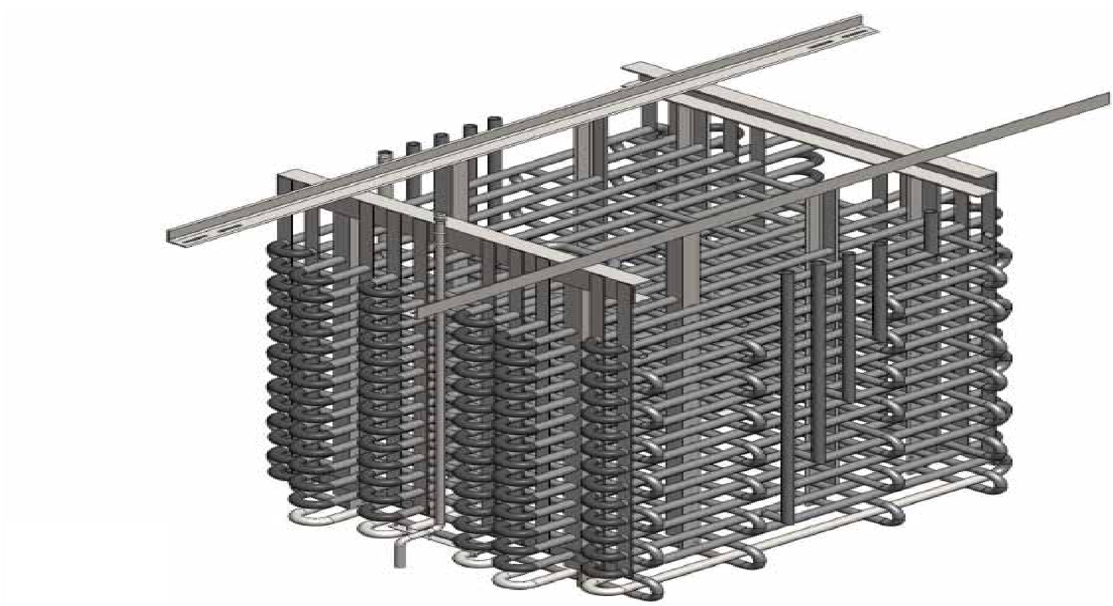
The main benefit to the customer is that the results from the Elvington trials will underpin the Pre-Commissioning Safety Report and will allow transportation of the Waste Skips using the onsite road network.



Customer Commendation

Customer feedback to NNL for our successful delivery of the SEP Skip Liquor Containment Trials was amongst the best received from a customer during the year. All aspects of the project were rated as 'very good' (the highest rating possible). We are proud that such glowing feedback has been received.

SEP Skip Liquor containment test rig assembly



Rig Simulation of the Re-suspension of Solids in HAL Storage Tanks

A smaller scale mock-up saved time and money while providing accurate and important results

Highly Active Liquor (HAL) has been stored safely on the Sellafield site for many years in large circular storage Highly Active Storage Tanks (HASTs). The liquid waste is kept cool by a series of cooling coils within the tank, and any residual solids within the liquor are kept in suspension by means of a number of jet ballast tanks and air lifts. The programme to vitrify these liquors is making good progress and as a result these tanks will soon near the end of their operational life.

As the HAST tanks are finally emptied as part of the Post Operational Clean Out (POCO) phase the hydraulic efficiency of the jet ballast tanks and air lifts may reduce as the liquor level falls. This could lead to an increase in the solids loading of the residual heel liquor. Hence there is a requirement to investigate and better understand the re-suspension of solids as the liquor level changes in support of plant operation and POCO on the Sellafield site.

After conducting re-suspension trials on simple 1/10 scale models, NNL conducted a fluid dynamics study and concluded that a 4/10 scale mock up of the HAST storage tanks was the most effective scale for studying the clearance behaviour of solids from the base of these large tanks. At this scale water can be used as the HAL liquor simulant and still exhibits the same fluid dynamic properties rather than having to use more exotic simulants at full scale.

NNL designed, built and are conducting solids re-suspension trials on a 4/10 scale mock up of a HAL storage tank. This tank contains scaled mock ups of the cooling coils, seven jet ballast tanks, air lifts and other in tank furniture. The tank itself is made entirely from transparent acrylic and is mounted 2m above the floor, allowing the solids clearance patterns produced on the base of the tank to be observed directly from below when the jet ballast tanks are pressurised.

The rig has all the necessary pipework, pumps and instrumentation to fire up the jet ballast tanks, the order and timing of which can be altered by the Labview based control and data acquisition system. Video cameras are located below and around the tank to observe the clearance and re-suspension patterns produced. These images are then reviewed automatically by video analysis software to compare the various results.

This project has already provided Sellafield Ltd with quantitative trial data on the behaviour of the re-suspension of solids from the base of the circular HAL storage tanks when altering the various parameters such as jet positions, flow rates, pulse durations, solids loading and liquor levels.

Building a full scale mock-up would have been prohibitively expensive due to the amount of simulant required. Therefore, building the rig at 4/10 scale has provided a cost effective solution to allow Sellafield Ltd to update and modify their models of the actual tanks behaviour on site and investigate tank behaviour during the POCO stage. This will enable Sellafield Ltd to develop the optimum strategy for the final emptying of the actual tanks.

Improving Visibility in Pond Water

A joint venture made novel use of technology to kill algae and improve visibility in storage ponds - making operations safer and more efficient

NNL's challenge was to improve and control the visibility in the First Generation Magnox Storage Pond (FGMSP) located at Sellafield. The two main issues that contribute to poor visibility in the fuel storage pond are:

- Growth of algae within the ponds
- Large amount of sludge present on the floor (including dead algal biomass), which becomes suspended once disturbed during retrieval operations

NNL carried out a trial as part of a joint venture with NDX Solutions™ to assess PDX® reactor technology for improving pond visibility. This technology introduces steam into a fluid at high-speed generating high levels of shear forces and turbulence within the process fluid which leads to the creation of controllable, cross bore condensation shockwaves.

The reactor should therefore be capable of destroying algae present in the storage ponds. It should also be able of fast and efficient mixing of powders with liquids, being ideal for introducing flocculating agents to the ponds for treatment of particulates. As a result, trials were set up to determine the ability of the PDX reactor to:

- kill algae when the temperature is raised above 70°C and identify an optimum kill temperature
- increase algal and sediment flocculation following introduction and mixing of a flocculating agent

The ability to improve and control the visibility of the pond water will assist Sellafield Ltd in determining the most effective and efficient way to decommission the FGMSP. The successful application of this technology for improving visibility in the FGMSP would provide evidence for utilising this technology for the treatment of other storage ponds with similar visibility issues.

Economics of Spent Fuel Storage

NNL carried out a data review of long term storage options to help the NDA develop their strategy for Spent Oxide Fuel

The NDA are developing a strategy for Spent Oxide Fuel and NNL is supporting this endeavour. Currently the preferred option for spent fuel is long term interim storage followed by disposal in the Geological Disposal Facility (GDF). However, there are still many potential option variants associated with long term interim storage with the supporting option information coming from a variety of sources. This makes analysing and comparing these options and scenarios difficult and means that issues such as potentially incomplete data have to be explored in detail.

The NDA asked NNL to conduct a data review of the main long term storage options covering:

- Wet Storage
- Dry Storage in vaults
- Dry Storage in casks

This was to enable analysis of different scenarios for the storage and packaging facilities. Additionally the NDA asked that socio-economic data was considered to enable an informed analysis of non-financial aspects for the options and scenarios.

NNL was able to draw on a range of expertise from across the business to carry out this data review. Worldwide data sources were examined. These sources gave a range of financial information for long term storage activities based on relevant existing plants (ie both recently constructed plants and plants built in the 1970s), on fully designed plants yet to be operated and on feasibility studies. Depending on the age of the associated study, the closeness of fit to a UK designed facility and whether the facility had actually been built, these criteria enabled a classification of the quality of data and allowed the comparison of different financial cost data sets for similar facilities.

This comprehensive data analysis was then incorporated into an economic model developed by NNL and can be used to compare different fuel storage scenarios (including MOx storage to support the UK Government policy of plutonium re-use).

Initially, this analysis has brought together information from a wide range of relevant data sources. This has enabled a comparison of the data quality and identified where further analysis is required. Development of the economic model has also helped to identify those assumptions crucial to understanding the detailed financial implications of spent fuel storage.

Modelling Activity Transport Behaviour in PWRs

As part of an international project, NNL has helped develop a model to help predict activation behaviours in Pressurised Water Reactors

The activation and transport of corrosion products around a PWR circuit is a major concern to reactor operators as these may give rise to high personnel doses. The understanding of what controls dose rates on ex-core surfaces and shutdown releases has improved over the years but still several questions remain unanswered. For example, the relative importance of particle and soluble deposition in the core to activity levels in the plant is not clear. There are wide plant-to-plant and cycle-to-cycle variations which are currently unexplained.

Over the past few years an international group consisting of NNL, EDF (France), EPRI (USA) and Vandellòs (Spain) has been collaborating on the development of models to simulate corrosion product transport around a PWR circuit. These models form the basis for the latest version of the BOA code and simulate the movement of corrosion product species around the primary circuit.

Recent developments to the modelling of release, speciation, transport, in-core activation and subsequent ex-core redistribution of both soluble and particulate components have been presented at an international conference on water reactor chemistry.

The model has been applied to explain the plant behaviour at Sizewell B and Vandellòs II. This model accounts for activation in the core, soluble and particulate activity movement around the circuit and for activity capture ex-core on both the inner and outer oxides. The model gives a reasonable agreement with plant observations and highlights what controls activity transport in these plants and importantly identification of the dominant factors which may be incorporated within plant management strategies.

Space Batteries

NNL is developing a process that can be used to help power long distance space missions

Using radioactive isotopes to generate energy that can be used to power future space missions is an exciting area of science. NNL is developing a new process called AMPPEX (Americium and Plutonium Purification by Extraction) that can be used to isolate 241-americium from plutonium for use in space batteries.

Traditionally, solar panels have been used on space missions to provide energy for spacecraft instruments and communication devices. A downside of solar panels is that they struggle to meet the power demands once the distance from the sun is too great. This problem can be overcome by using a radioisotope as a power supply in a space battery.

Space batteries provide energy regardless of the distance from the sun, allowing ventures into deeper space. An example is the Voyager 1 satellite which was launched in 1977 and is now more than 18 billion miles from the earth. As a result of the long lived space batteries, communication with the satellite is still possible despite it being about to leave our solar system.

Space batteries use thermocouples to convert the radioactive alpha decay energy into electricity. Significant engineering challenges need to be overcome to ensure that there is no risk of accidental radioisotope release. Maintaining structural integrity at all times is vital and the fuel pellet is contained within several different layers of protection.

During previous space missions 238-plutonium has been used as a radioisotope power source. Within Europe there are no facilities for 238-plutonium production and therefore an alternative is needed. 241-americium has been identified as a possible option. This americium isotope is formed from the radioactive decay of 241-plutonium within plutonium dioxide which itself is a product from reprocessing spent civil nuclear fuel at Sellafield. The challenge is to separate americium from the plutonium dioxide and work has begun to demonstrate a process for this using solvent extraction chemistry.

The fundamentals of solvent extraction chemistry revolve around the solubilities of species in a two-phase aqueous/solvent system. Aqueous acid is generally used to bring all of the metal ions into solution. When vigorously mixed with a solvent phase containing receptor molecules the selective extraction of metal ions (from the aqueous to the solvent) takes place. The ions that are not extracted by the receptor remain in the aqueous phase and the first step towards separation is complete. Backwashing occurs when extracted metal ions in the loaded solvent are washed back into an aqueous phase. Generally, it is preferable to end up with the separated ions in the aqueous phase as this allows for subsequent ease of handling and processing.

The successful extraction of target ions relies entirely on the behaviour of the receptor and several criteria need to be met: a) the receptor needs to be selective for the target ion(s) to enable its separation; b) the resultant receptor-ion complex that forms needs to be solvent soluble; c) the complex formed should not be too strong as subsequent decomplexation (backwashing) and release

of the target ions is necessary; d) the receptor needs to be radiation resistant, acid resistant and synthetically accessible.

Solvent extraction is already a well established technology within the nuclear industry. The PUREX process (plutonium uranium extraction) uses a tributylphosphate (TBP) receptor and a nitric acid/ odourless kerosene (OK) aqueous/solvent system. Spent nuclear fuel is dissolved in nitric acid then mixed with TBP/OK. This enables the selective extraction of U(VI) and Pu(IV) from a mixture of fission products that are present in dissolved spent fuel. The uranium and plutonium are then separated and undergo further purification processes to produce a product that is suitable for safe, long term storage.

To use 241-americium in a space battery requires its separation from stored plutonium dioxide. The first step is to dissolve the plutonium dioxide in nitric acid. Silver is used as a catalyst to aid dissolution. The silver then needs to be separated from the dissolved plutonium and americium. A two stage solvent extraction process has been considered. The first solvent extraction separates plutonium from a mixture of plutonium/americium/silver and the second separates americium from the remaining americium/silver mixture. Using receptor molecules that are selective for each element facilitates separation and three product streams are produced one for each of plutonium, americium and silver. Not only does the AMPPEX process produce pure 241-americium, it also produces plutonium that is less radioactive and easier to handle.

For future European Space Missions 241-americium is a promising option as a radioisotope power source. As the isotope is already present in stored plutonium dioxide it is not sustainable indefinitely unless there is a large stock available. Furthermore, it is an example of how established solvent extraction technology can be extended and developed to new applications.

$^{238}PuO_2$ pellet used in Radioisotope Thermoelectric Generators (courtesy of NASA)

Working with UK Government

As the UK's National Nuclear Laboratory, we work closely with Government across a number of strategic areas

Following discussions between UK Government and NNL around the overall requirements for the UK Research & Development Advisory board set up under Sir John Beddington, NNL was asked to provide three secondees to assist the Department for Business, Innovation and Skills (BIS) and the Department for Energy and Climate Change (DECC) to fully define the board's key requirements. The three areas were:

- R&D Landscape - covering capabilities, R&D programmes and facilities
- Industrial Vision - supporting BIS to develop an R&D vision for industry working with Government to create growth opportunities for the UK
- R&D Roadmap - supporting DECC to define the various scenarios and options to 2050 and beyond

Landscape Review

NNL provided support to the Government Office for Science (Go-Science) throughout the preparation of a review of the UK's current nuclear R&D capability - published in March 2013. The review provides a baseline against which decisions about the future scope and scale of support to this sector can be taken. It provides a detailed snapshot of current policy, existing R&D strategies, the R&D funding system, capability in terms of both personnel and facilities and finally coordination and collaboration within the R&D system.

Industrial Vision

NNL assisted BIS in developing two key documents relating to the future of the nuclear industry in the UK: the Nuclear Industrial Vision Statement and the Nuclear Industrial Strategy. The vision, written with extensive industry input, sets out the UK nuclear industry's aspirations in the nuclear sector in domestic and global markets to 2050, detailing what is required to enable this.

Following on from the vision, and drawing from a number of other reports including the R&D Landscape and Roadmap, was the Nuclear Industrial Strategy. The Strategy identifies priorities that Government and industry will work on together in a long-term partnership with the aim of providing more opportunities for economic growth and creating jobs through an increased share of all aspects of the nuclear market. The new Nuclear Industry Council, on which NNL sits, will own this Strategy, driving forward the work programmes and keeping it current.

NNL seconded an employee into BIS full time for 10 months to work in the team coordinating the production of these documents. In addition, members of NNL's Senior Management were part of the industry groups which were consulted, and provided a valuable steer as to the direction which NNL should take in support of the UK's nuclear energy and commercial objectives in the future.

Roadmap Development

NNL has provided support to DECC throughout the preparation of a UK nuclear R&D roadmap - published in March 2013. The roadmap sets out the research outcomes which would support implementation of future technology pathways. Detailed illustrative timelines have been developed as examples of these pathways. The three main pathways which were considered were:

- Baseline - which illustrates the R&D requirements which are needed to support the existing reactor fleet, decommissioning, clean-up and geological disposal programmes
- Open fuel cycle pathway supporting 16-75 GW of new nuclear generation capacity
- Closed fuel cycle pathway to the same levels of generation

The roadmap was developed following an initial R&D landscape review which documented the current nuclear R&D position within the UK.

Nuclear Research and Development - Support to DECC

NNL has provided significant support to DECC in helping to develop a national programme of nuclear R&D. The key objectives are:

- Strategic Assessment - evaluation of a range of reactor systems and associated fuel cycles
- Fuels - retain skills in Pu fuel fabrication technology and fuel performance
- Reactors - develop the skills needed to evaluate potential future UK exploitation of advanced reactor system technologies
- Recycle - raise the overall technical maturity of both aqueous and non-aqueous recycling technologies

The work has identified a number of key outcomes which the UK will need to address.

Working with Academia

NNL works closely with a range of academic institutions, acting as a conduit between academic research and industrial application

A core part of NNL's remit is to undertake applied R&D, acting as a conduit between academic research and industrial application. As such, we continue to develop a wide range of links with Universities and have around 50 NNL staff with formal roles at a number of Universities including visiting professors, lecturers and fellows. We have strategic agreements in place with six Universities: Manchester, Liverpool, Leeds, Imperial College, UCLan and Sheffield and links with 20 others.

NNL sponsors and is involved in a number of research projects and consortia for example BIGRAD, MBase, NNUMAN and REFINE. These support our self investment R&D programmes as well as those funded by our customers. We also play a key role engaging with Universities and the academic community. One example was our involvement in the 1st UK Nuclear Academic conference held at St Annes in Oxford during September 2012. The meeting was sponsored by Professor Robin Grimes who is Principal Investigator of the Research Council's UK Nuclear Fission Champion Consortium Project. There were approximately 90 attendees, with around 80 from academia. NNL chaired the Fuel Material and Reprocessing sub-Group tasked with developing the 'Grand Challenges' for the area, from an academia perspective.

A new 'National Nuclear User Facility' (NNUF) has been agreed to expand academic and industrial nuclear research involving the handling and characterisation of radioactive materials. The NNUF will be centred at the three complementary hubs of the NNL Central Laboratory, Culham Centre for Fusion Energy and the Dalton Cumbrian Facility. The proposal is led by Professor Robin Grimes from Imperial College London (PI) and has been developed in partnership between NNL, Culham, the University of Manchester, University of Oxford and Imperial College London.

NNL is always seeking ways to make use of its facilities more accessible to UK universities, with the vision of creating a seamless boundary between NNL and those universities with interest in nuclear research. Two Universities, Manchester and Liverpool, have formal agreements in place to enable access to our Central Laboratory and a number of students have worked in our laboratories over the past year. There are a number of other Universities that have expressed an interest in seeking access through the existing third party access arrangements.

Engineering Doctorate Schemes

NNL is an industrial partner and member of the management board of the Engineering Doctorate (EngD) in Nuclear Engineering. A consortium of eight UK Universities, led by The University of Manchester in partnership with Imperial College London, delivers the EngD in Nuclear Engineering.

The EngD is a four year research programme that combines the academic strengths of a conventional PhD with a taught programme which develops technical, business and personal skills. The primary objective is to provide outstanding young nuclear Research Engineers with intensive, broadly based training in collaboration with industrial companies so that they are equipped to take up senior roles within the nuclear industry. Since 2006, NNL has sponsored five EngD's in Nuclear Engineering.

REFINE Research Programme

REFINE is a multidisciplinary programme aimed at enabling advances in UK molten salts skills and capability

Reduction of Spent Fuel Vital In a Closed Loop Nuclear Energy Cycle

REFINE is a coordinated UK research programme delivering the materials science required for sustainable spent fuel reduction in a closed loop nuclear energy cycle. This multidisciplinary programme aims to deliver the critical academic research team and the platform technologies to enable scientific advance in related molten salt application areas together with the underpinning process development and training essential to establish and deliver these objectives. It is the first step in developing transferable UK molten salt skills and capability, which is a requirement identified in the UK Nuclear Fission Technology Roadmap.

The programme is focused on the fundamental research, understanding and essential systems required in the development of a viable molten salt spent fuel treatment facility. It consists of an integrated programme of three work packages, each addressing a key theme with its identified global and specific objectives.

- Direct electrochemical reduction - understanding and controlling interactions in molten salts, forming solid state materials cleanly and efficiently, specifically electroactive materials for enhanced electrochemical separation in the electrorefiner
- Electrorefining and speciation - specific solid state materials production by dissolution and deposition of selected species with controlled composition and morphology, specifically ensuring proliferation resistance. Dissolution of stable materials, specifically Gen IV fuels (ceramic, nitride and carbide fuels) and production and characterisation of the molten salt soluble species
- Analysis - establishment of molten salt analysis techniques, specifically the in-line sensing technology required for pyrochemical reprocessing systems with modelling to understand molten salt fundamentals and materials processes

The REFINE consortium is led by the University of Edinburgh and includes the Universities of Cambridge, Manchester, Nottingham and University College London, in partnership with NNL.

NNL provides industrial focus and access to active and inactive pyrochemical facilities. Access to the unique and specialised Molten Salt Dynamics Rig provides an engineering, pilot plant, scale industrial based unit to support development of inline monitoring and analysis and engineering skills.

Working with Europe

NNL plays a leading role in a range of European projects for the benefit of the UK

ACSEPT

The ACSEPT (Actinide Recycling by Separation and Transmutation) project ran for four and a half years from 2008 until 2012. Funding was provided by the EU, Sellafield Ltd and the NDA (through its Direct Research Portfolio). The project researched new ways to reduce the inventory of radioactive waste and contribute to sustainable nuclear energy. NNL was a major project partner, working alongside over 20 European laboratories and universities. NNL's 'PuMA lab' was used to carry out experimental work for the ACSEPT project towards developing a GANEX (grouped actinide extraction) process. While the separation of U and Pu is well established ,there remains a challenge to recover the remaining actinides, particularly from the chemically similar lanthanides. The aim of GANEX is to extract all of the actinide species in solution into a solvent (offering proliferation resistance) and then selectively backwashing to produce a separate actinide product. In collaboration with researchers in Germany and France, work progressed from small scale batch reactions, in which the experimental variables were determined, to several rig trials in which the behaviour of the full separation process was studied. For further information, please visit: www.acsept.org

ASGARD

ASGARD (Advanced Fuels for Generation IV Reactors: Reprocessing and Dissolution) is a four year programme and work began in 2012. Programme funding is provided by the EU, NNL and NDA. It focuses on advanced/novel nuclear fuel for Gen IV reactors focusing on their fabrication and respective reprocessing issues. ASGARD seeks integration between reactor, fuel and recycling communities and is an international effort of 16 institutions from 9 European countries. NNL's involvement is with the fabrication and reprocessing of carbide fuel. Specifically, NNL plans to use the PuMA lab to investigate the dissolution behaviour of carbides. For further information, please visit: http://asgardproject.eu/

SACSESS

Work on SACSESS (Safety of Actinide Separation Processes) began in March 2013. Among the different strategies studied to manage nuclear waste, partitioning and transmutation (P&T) allows a reduction of the amount, the radiotoxicity and the thermal power of wastes, leading to optimal use of the geological repository sites. SACSESS will provide a structured framework to enhance the fuel cycle safety associated P&T. By optimising the safety of both aqueous and pyro separation processes, it will allow actinide recovery on a sound scientific and technical basis. All these data will be integrated to optimise flowsheets and process operation conditions. SACSESS will be dedicated to safety and focus on the optimisation and improvement strategy on the basis of the existing systems.

CARBOWASTE

This European collaborative research project 'Treatment and Disposal of Irradiated Graphite and other Carbonaceous Waste (CARBOWASTE)' commenced in 2008, and will complete in 2013. The aim of the project is to develop best practices in the retrieval, treatment and disposal of irradiated graphite, addressing both existing legacy waste as well as waste from graphite-based nuclear fuel resulting from a new generation of nuclear reactors. The consortium is led by Forschungszentrum Juelich (FZJ) in Germany and involves 28 partners from Belgium, France, Germany, Italy, Lithuania, Netherlands, Romania, South Africa, Spain, Sweden and the United Kingdom. NNL is leading the Integrated Waste Management work package. The Carbowaste project is building a harmonised 'tool box' of techniques, methodologies and best practices for decommissioning and waste management of irradiated graphite, that can be applied to the specific needs and conditions within a country and site. For further information, please visit: http://www.carbowaste.eu/

GoFastR

GoFastR (Gas-cooled Fast Reactor) is a three year programme that began in 2010 and will conclude in 2013. Funding is provided by the EU and through NNL's Reactors and Fuels Signature Research Programme. The Gas-cooled Fast Reactor (GFR) is a Generation IV reactor design that is being developed in order to be safe, sustainable, economic and proliferation resistant. In particular, GFR could be capable of operating at very high temperatures (higher than other fast reactors), allowing for more efficient electricity generation and the supply of process heat for other applications such as hydrogen gas production. The GoFastR project has focused on the development of the designs for GFR and the ALLEGRO demonstrator reactor with contributions from 22 institutions across 9 European countries. NNL has contributed a strategic assessment of the potential impact of GFR in the fuel cycle, a fuel performance assessment of the MOX fuel proposed for the first lower temperature core of ALLEGRO and a review of advanced cladding materials for the subsequent higher temperature ALLEGRO cores. NNL's work for the project has now been completed.

Senior and Research Fellows

We appoint a number of senior roles to ensure our research is led by experts in the key areas of development needed to support the UK nuclear industry

The role of Senior Fellow is well established in NNL. These are people who are at the forefront of their area of expertise. We have Senior Fellows appointed for 7 areas:

Colin English, Materials
Robin Taylor, Actinides
Kevin Hesketh, Reactor Physics
Richard Taylor, Engineering
Guy Whillock, Corrosion Science
Joe Small, Waste and Environmental Geochemistry
Martin Metcalfe, Graphite

Each of our 7 senior fellows has links with universities and a number of other staff hold various visiting appointments. We have formal memoranda of understanding with 6 universities: Sheffield, Leeds, Liverpool, Lancaster UCLan and Imperial and links with a number of others.

We provide technical leadership and industrial supervision of the 29 PhD students funded under the NDA bursary scheme and there are 27 CASE award studentships at various stages (from awarded but not yet commenced through to thesis submitted) who are being supervised by our staff. In addition, we have hosted two EngD students on long term secondment into our teams, one of whom has now submitted his thesis.

We have also appointed 24 academic associates, and one of these, Jon Lloyd of the University of Manchester has been seconded into NNL for 50% of his time. In addition, we have 10 RAEng fellows at these and other universities.

Role of Research Fellows

As part of their role, NNL Research Fellows will:

- Be assigned to a specific research area to work for a 4 (financial) year tenure
- Be expected to spend at least 5% of their available time per year supporting universities
- Be linked to a nominated university
- Be expected to gain visiting status within the first year of their tenure at the nominated university
- Be required to visit the nominated university at least 6 times per year
- Create and submit at least 1 joint proposal per year to UK or EU research councils that provides funding to support research within a NNL signature research area and is connected to their research area
- Publish at least 1 joint journal paper in per year connected to their research area

Working with Others

NNL is an active participant in the international conference scene and makes presentations about the latest developments in our sector

NNL attends, presents and exhibits at a range of national and international conferences. Our technical experts are called on to share their views around the world.

Some of the conferences we have attended this year include:

- Serco Science Community Early Career Conference
    - » NNL is part of Seco's Science Community and this event presented an opportunity for some of our younger scientists to share work and experiences with others across the community - including the National Physical Laboratory, Atomic Weapons Establishment and Serco Energy
- International Nuclear Fuel Cycle to support new build reactors
    - » Held in Manchester, this conference saw 12 attendees from NNL. Most were joint authors of a paper titled "Hot Isostatically Pressed Wasteforms for Future Nuclear Cycles"
- Top Fuel 2012
    - » Focused on the challenges facing the developers and manufactuers of new high-performance nuclear fuels. NNL presented papers on "Analysis of Fission Gas in AGR Fuel" and "Understanding advanced gas cooled reactor (CAGR) fuel using metallography"
- NETS 2013 - Nuclear and Emerging Technology for Space, USA
    - » NNL presented an update on our progress on Am-241 production for use in Radioisotope Power Systems.
- European Nuclear Conference
    - » One of the major European conferences, this presents a unique EU wide opportunity to network with key scientists and technologists. In addition to a paper on our Space Batteries project, NNL also presented on "Monitoring and Inspection Techniques for Long Term Storage of Higher Activity Waste Packages"

RoSPA 2011
Winner
RESEARCH & DEVELOPMENT
Sector Award

Winner 2004 - 2008, 2010 - 2011
Highly Commended 2009, 2012, 2013

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